Using a Web GIS Plate Tectonics Simulation to Promote Geospatial Thinking

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ABSTRACT

Learning with Web-based geographic information system (Web GIS) can promote geospatial thinking and analysis of georeferenced data. Web GIS can enable learners to analyze rich data sets to understand spatial relationships that are managed in georeferenced data visualizations. We developed a Web GIS plate tectonics simulation as a capstone learning activity in an undergraduate Earth Science course that integrated geological and geophysical data sets to allow students to dynamically reconstruct ancient plate motions. To assess the effectiveness of the Web GIS tectonics simulation, all 12 students in the course submitted three artifacts that were assessed with a reliable, criterion-based rubric. The students also completed a survey to assess the effectiveness of the online interface and its capability to promote geospatial thinking. The students preformed quite well on the assignment. The survey results supported that the students perceived the Web GIS tectonics simulation as having helped them think geospatially. Our Web GIS design and embedded capabilities allowed students to advance and confirm their understandings about the tectonics concepts. Student responses indicated that the Web GIS supported their geospatial analysis for making inferences about space, geospatial patterns, and geospatial relationships among the data that were visualized in the Web GIS. Design features that contributed to the successful implementation are discussed.
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Key words: GIS, Web GIS, plate tectonics, geospatial thinking

INTRODUCTION

Spatial thinking is inherent to the geosciences for both experts in the field and for novice learners (Manduca and Kastens, 2012). Spatial thinking is characterized by understanding the nature of space, the methods used to represent spatial information, and the processes of spatial reasoning (National Research Council, 2006). Spatial thinking includes spatial knowledge of orientation, scale, distance, site, association, and other elements involved in a spatial reference frame (Tversky, 1996). It also includes spatial ways of thinking and acting, such as understanding change over space versus change over time, recognizing patterns in data, and using cognitive strategies to facilitate problem-solving and decision-making (Schultz et al., 2008; Titus and Horseman, 2009; Liben and Titus, 2012). In the geosciences, spatial thinking involves abilities and skills that recognize spatial distribution and spatial patterns, identifying shapes, associating and correlating spatially distributed phenomena, imaging maps, and comparing maps and map imagery. These spatial abilities involve cognitive processes such as spatial perception, mental rotation, and spatial visualization (Kastens and Ishikawa, 2006). The ability to visualize spatial relations—such as object shapes, relative locations, and how these change over time—is a fundamental skill necessary to understand and reason about geoscience concepts (Ormand et al., 2014). Studies that have used standardized psychometric measures of spatial skills have found that spatial ability has a critical role in developing expertise in science, technology, engineering, and mathematics (STEM) outcomes (Wai et al., 2009) and has been linked to earned undergraduate and graduate degrees in STEM and the pursuit of professional STEM careers (Shea et al., 2001).

Spatial thinking processes that are bound by the Earth's surface, or to the Earth's representation through maps and computer displays are classified as *geospatial thinking*, a subset of spatial thinking (Huynh and Sharpe, 2013). Geospatial thinking involves using tools of representation for making inferences about space, geospatial patterns, and geospatial relationships related to the Earth's surface. These representations include map and globe visualizations that are used as tools to organize and understand data that are georeferenced to the Earth's surface. Thinking geospatially requires knowing, understanding, and remembering geospatial information and concepts. It provides a way of examining data and information that reveals properties or relations about the Earth's surface that may or may not be readily apparent. It also involves cognitive processing of georeferenced data that have been encoded and stored in memory or that are represented externally to the mind by map visualizations (Uttal, 2000). In the geosciences, the capacity to visualize data patterns and relationships on the Earth's surface is integral to the process of geospatial thinking and involves geospatial abilities such as geospatial visualization, orientation, and geospatial relations, which can be facilitated by a geographic information system (GIS) (Albert and Golledge, 1999).

Educators have recognized that GIS has the capacity to promote teaching and learning by (1) enabling powerful, multidisciplinary visualization, analysis, and synthesis of data; (2) expanding student understandings of important discipline-based content; and (3) enhancing inquiry in the

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sciences (National Research Council, 2006; Baker et al., 2012; Bodzin et al., 2015). GIS is a class of software applications that organizes Earth's features into thematic layers and then uses computer-based tools to aid in examining and analyzing spatial patterns, linkages, relationships, and trends. The GIS tool set enables learners to view, manipulate, and analyze rich data sets from local to global scales, including data related to geology, seismic hazards, flora and fauna distribution, climate, land cover, infrastructure, and other data that can be georeferenced using two- and three-dimensional, visualization and analytical software. GIS visualizations and their interactive visual interfaces can effectively provide material for spatial analysis and reasoning in geospatial contexts (Andrienko et al., 2007). This may involve investigating anything that can be displayed on maps, databases, images of the Earth's surface, graphs, and in other ways, and that can be studied geographically (Baker et al., 2012). Studies at the secondary level have found that appropriately developed curriculum using GIS can address students' misconceptions pertaining to the influence of physical geography on temperature over long timescales (Edelson et al., 2002), improve data analysis skills (Baker and White, 2003), and enhance energy content knowledge (Bodzin et al., 2013), climate change understandings (Bodzin and Fu, 2014), and geospatial thinking and reasoning skills (Bodzin et al., 2014).

Web-based GIS (referred to as Web GIS) is a form of GIS that is deployed using an Internet Web browser. Web GIS offers some of the same functions as desktop GIS but does not require the full suite of, often expensive, specialized software or tools that need to be mastered before one may effectively use the software. It provides a scale-independent tool that allows users to manipulate and analyze very large data sets to discover geospatial patterns related to location. Recent Web GIS development capabilities that include the use of JavaScript APIs can provide for the customization of both the Web GIS interface and tools to reduce the cognitive load that learners may experience when compared with typical, desktop GIS software applications that are designed for industry and not for use in typical educational settings (Bodzin et al., 2015).

Learning with Web GIS can involve investigating phenomena related to the Earth's surface and entails understanding geospatial data, patterns, and relationships. This involves a skill set that includes geospatial thinking and analysis, critical thinking, and inquiry-based learning. When using a Web GIS in a geospatial learning activity, students are involved with examining, querying, analyzing, and editing geospatial data. Web GIS can enable learners to geospatially analyze rich data sets to understand complex patterns that are produced in data visualizations. Being able to visualize and manipulate data can increase students' ability to transfer new knowledge to novel situations (National Research Council, 1999) and can help students understand interdisciplinary science and social science concepts (National Research Council, 2006). Therefore, designing learning environments with Web GIS can create meaningful contexts for learning by providing emphasis on critically important science thinking skills and enhance learning by adding an emphasis on geospatial thinking. Such designs hold promise for promoting geospatial thinking with learners to enable knowledge about space and representations to be combined for problem-solving and decision-making.

The use of Web GIS in instructional settings has been increasing since the accessibility of Web services, and new tools have made it easier for instructional designers to develop and use existing geospatial applications for the Web, share geospatially referenced content, and create visualizations that make data patterns and relationships more readily apparent. Although the published literature has described Web GIS learning initiatives (e.g., Henry and Semple, 2012; Kim et al., 2013), there have been very few published efficacy design studies that have tested the use of Web GIS in educational learning settings. Bodzin et al. (2015) conducted an implementation study of a series of Web GIS tectonics investigations designed to enhance a typical Earth Science curriculum in an urban school district with middle-level students. The tectonics Web GIS learning activities were developed using a curriculum design approach for geospatial thinking and reasoning. The findings from pretest and posttest tectonics content knowledge and geospatial thinking and reasoning achievement measures revealed statistically significant gains from pretest to posttest with large effect sizes. Data from the classroom observations showed that most students were actively engaged in the learning tasks, investigated driving questions that involved geospatial thinking and reasoning skills, and learned important concepts about tectonics and seismic hazards. The study reported that the scaffolding within the instructional materials themselves, in addition to classroom modeling by the teacher, was needed to assist students with completing the geospatial analysis tasks.

Because the use of Web GIS with appropriately developed instructional materials holds promise to promote important spatial thinking skills related to the geosciences, we developed a Web GIS plate tectonics simulation based on a tried-and-true, paper-and-pencil, simulation learning task to use with advanced undergraduate students in the geosciences. The purpose of this project was to develop a Web GIS user-friendly interface and create a novel learning environment for students to discover important geospatial relationships among tectonics data using Web GIS mapping and analysis tools, which included a series of instructional supports designed to help promote geospatial thinking skills. We were also interested in understanding how the Web GIS simulation helped our students think geospatially about data related to tectonics.

THE WEB GIS PLATE TECTONICS SIMULATION

The Web GIS plate tectonics simulation is a capstone learning activity that integrates geological and geophysical data sets to allow students to reconstruct ancient plate motions in an authentic fashion. We designed the Web GIS interface to be user friendly for the students and developed a suite of tools to aid students in their geospatial explorations. Each student was provided with a personalized login to access the Web GIS. This allowed students to save their work, including visualizations, and return to it later. We also developed a detailed instructional handout for the students and a series of instructional videos that highlighted how to use the Web GIS tool features. These are placed on a Web site and can be accessed by students at any time. We purposely provided the learning materials and instructional supports to be Web-based to enable our students to complete the simulation activities at their own pace and to aid in the dissemination of curriculum materials.

GEOLOGICAL AND GEOPHYSICAL DATA

In the learning activity, students use geological and geophysical data in a Web GIS to discover modern plate boundaries by identifying ridges, transforms, and subduction zones; drawing isochrons to delineate the ages of the ocean floor; and reconstructing ancient continent positions. The data sets included were all georeferenced and internally consistent. The continental data sets included topography, 3 ages of mountains, sedimentary basins, faults, aulacogens, earthquakes, and paired coastline shapes as well as truncated geologic features, which provided clues to the final reconstructions (Fig. 1). Young mountains in the center were contrasted against older, rifted mountains at the top. The topography of the continents was a composite of natural examples. For example, Fig. 1 illustrates the volcanic topography typical of an island formed above a midocean ridge.

The marine data sets were presented beneath an opaque ocean with the exception of earthquake epicenters. Shallow, extensional and shallow, strike-slip epicenters were reflective of ridge and transform boundaries, respectively, whereas deep earthquakes formed above subducting slabs. Earthquake focal mechanisms provided clues to the type of plate boundary each earthquake is associated with. The additional marine data could only be accessed as data recovered as ship tracks. Bathymetry was most useful for identifying midocean ridges and calculating spreading rates. Bathymetric data also demonstrated abrupt steps in the ocean floor at transform faults and the deep oceanic trench seaward of the convergent plate boundary. The magnetic anomaly data set showed natural fluctuations in the anomaly; polarity zones were symmetrical about midocean ridge segments with the polarity zones proportional to the spreading rate. When these are used in conjunction with the sediment cores, they allowed the learners to determine isochrones of the ocean age. Also, sediment cores faithfully depicted the thickness and sediment type, consistent with location within the ocean basin. For example, turbidities were reflective of proximity to continental areas and clay-rich sediments were reflective of oceanic deep water, far from land. The reported biostratigraphy provided the evidence of the age of the ocean floor. However, in realistic fashion, sediment cores came with a few biostratigraphic ages. Only sediment ages were provided and not oceanic crust ages. Oceanic crust is typically not drilled or analyzed for age. Therefore, the students had to make inferences about the age of the ocean given the age distribution of the sediment column in the drill cores.

Although the Plate Tectonics Web GIS activity we developed requires authentic data synthesis and interpretation, it uses a synthetic data set. We used the basic paleogeography of the earlier paper version activity, e.g. the Indian Ocean borderlands, and incorporated ocean floor bathymetries and focal mechanisms from the Atlantic for the spreading center and abyssal and subduction zone sedimentation from the western Pacific Ocean. Although the base map was not derived from a single natural place, most of the elements do come from natural examples.

LEARNING DESIGN

We designed the learning activity to take advantage of constructivist learning principles to promote an active learning environment (Bransford et al., 2000). During the simulation activity, students use active learning techniques that include manipulating multiple data sets to test their assumptions and authentic problem-solving to generate understandings about geospatial relationships and patterns within the Web GIS data. Using the Web GIS, students formulate, explore, and test their ideas, make inferences, and draw conclusions using personal visualizations. We dedicated two 3-hour laboratory class periods for students to complete the activity. The course was a standard sophomore or junior class level Structural Geology and Tectonics lecture and laboratory course that consisted of 28 hours of instruction. Each week contained 3 hours of lecture and 3 hours of laboratory contact. Typical students taking the course had completed an introductory course and a course in depositional processes. Most students in the class were also enrolled in an Earth Materials course and an Earth History course during the same semester. The tectonics content of the course dominated the final 5 weeks of lecture content but the "Plate Game" was the only active learning laboratory exercise. In the classroom, we provided students with an overview of the learning activity and highlighted some of the Web GIS tool features. This learning activity was also appropriate for junior level courses in Earth History, Marine Geology, or Plate Tectonics.

We designed the instructional handout and the videos to include specific scaffolding elements to assist learners with their progress through the different learning tasks. The instructional tasks that we ask of the students are complex learning tasks that they likely could not complete independently on their own without some form of assistance. We incorporated conceptual scaffolds (Krajcik et al., 1998) to help students organize their ideas and connecting them to related Web GIS data and we developed procedural scaffolds (Brush and Saye, 2001) to clarify certain tasks for the students. The videos included procedural scaffolds to illustrate important interface elements of the Web GIS and to model the use of specific Web GIS tools. Conceptual scaffolds were included in the videos that used illustrative examples to highlight some of the geospatial relations in the data. Scaffolding was used in specific locations in the instructional handout to help students master the content and to help them think about the geospatial patterns and relationships that were embedded in the data. Explanations and content-related information were included to move students along in the learning tasks. Other scaffolds included prompts, helpful hints, and suggestions that were designed to help students focus on geospatial relationships and patterns within the Web GIS data.

The week before the plate tectonics Web GIS was introduced, classroom lectures included such topics as Earth structure, plate boundaries, and divergent boundaries. During the week of the first laboratory session, lecture topics included passive margins, basin and range province, metamorphic core complexes and convergent boundaries. During the second week of the laboratory session, the lecture topics included accretionary tectonics and P-T-t (pressure, temperature, and time) paths. Additional tectonics lecture topics covered in the course include salt tectonics, plate circuits, and triple junction stability.

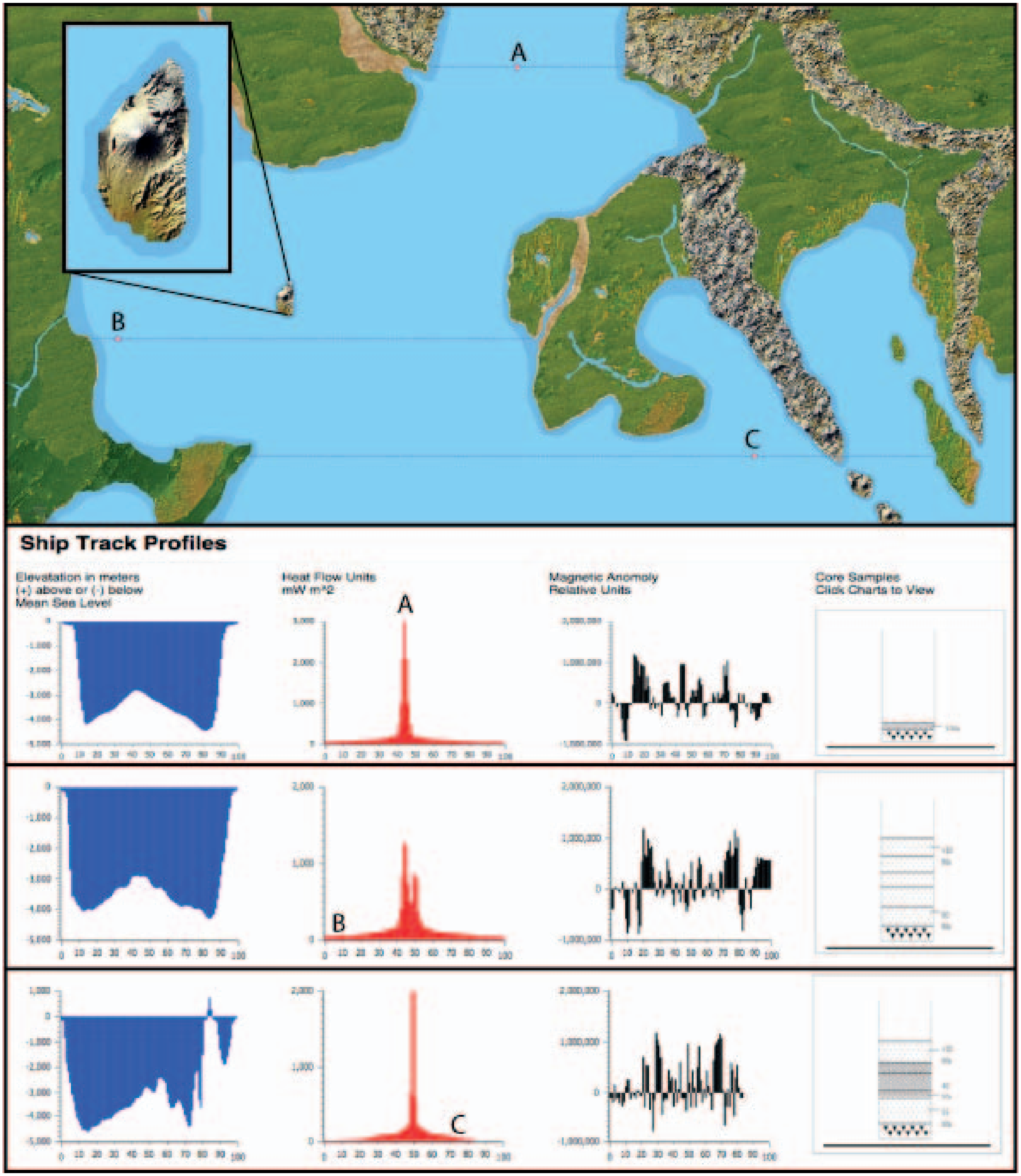

FIGURE 1: Base map for the learning activity, which shows digital elevation model topography, terrestrial basins, mountains, and coastlines. The marine data exist beneath an opaque ocean. Inset shows a volcanic island at enlarged scale. The map shows data collected from three ship tracks: A, B, and C shown. The marine data include, from left to right, bathymetry/topography along the chosen traverse, heat flow along the traverse, magnetic anomalies along the traverse, and sediment core from the location indicated by the dot. Sediment cores may be collected anywhere along the traverse. These ship tracks show examples illustrating slower (A) and faster (B) ridge spreading, younger (A) and older (B) examples of sediment cores, and a wide ocean being subducted (C).

TABLE I: Scaffolding examples from the Web GIS plate tectonics simulation instructional handout.

Example 1:
Ship tracks tell the ship where to go to collect data. The Profile Box contains the data pertaining to the ship track that you just drew. Keep in mind where you are leading your ship and how many tracks you need to use to gather data
Ship track locations should be a thoughtful choice. Inspect coasts to predict which way the oceans opened. Notice how different ship tracks look away from ridges, when drawn perpendicular to the ridge
Example 2:
Sediment cores
Sediment core samples can be taken at points along any of the bathymetry, heat flow, or magnetic anomaly graphs. Sediment cores reveal the age of the basement rock and the type of environment that has occurred at that location. Continental sediment shows exposure to continental crust. Sediment accumulation rates are a function of proximity to land and ocean age. Older ocean will be more covered in sediment than younger ocean.
Example 3:
Helpful hints:
Diagonal ship tracks may be misleading or hard to follow.
Very long ship tracks are good indicators of general trends, but they make it difficult to discover specific details in the track.
When hunting for ridges, try using shorter horizontal tracks.
To find transforms, try using longer vertical tracks. Transforms are perpendicular to ridges.
Remember that younger ocean floor is hotter and more buoyant than older ocean floor that has sunk and cooled
Sediment thickness, age of ocean, and bathymetry all co-vary; think about what patterns you might expect to see.
You are encouraged to make hypotheses and then confirm or modify them through data collection and analysis.

The plate tectonics Web GIS activity is a capstone learning activity for the course's plate tectonics content. It is most appropriate for use in a course that combines structural geology and tectonics, such as the course at our institution or in a discipline-specific plate tectonics class. It is a sophisticated learning activity most appropriate after the basic skills of geology and stratigraphy have been learned. This is because of the inclusion of earthquake focal mechanisms and sediment cores as data sets to be explored. Structural geology and tectonics packaged together or separately is a common requirement in most BA/BS curriculums. Most areas of the country are located far away from a modern plate boundary. Therefore, in-class exercises are an optimal way to illustrate many natural processes. Because of this, the exercise has wide applicability.

The introductory sections of the instructional handout were very guided and have students follow a set of procedural steps with accompanied images to observe topography and access and understand the marine data, earthquake data, and sediment cores. Table I provides three scaffolding examples from the introductory sections of the instructional handout to illustrate some of the different forms of scaffolding used. The text in Example 1 provides students with an instructional prompt that focuses them on analyzing ship track data patterns. This scaffold provides students with a prompt for deciding where to make ship tracks and a strategy for thinking about the data patterns that are displayed. Example 2 provides students with a procedural scaffold that incorporates explanations and important content information about sediment cores that are needed later for analyzing data patterns in the core samples. Example 3 provides students with a series of helpful hints to move them along with their learning tasks. Many of the provided hints that we included were designed to assist students to think about geospatial patterns and relationships within the Web GIS data.

Although the introductory sections of the instructional handout take a more guided inquiry approach, the remainder of the instructional handout takes a more open-ended exploration approach because the students use the Web GIS to produce three artifacts that will be submitted for assessment along with explanatory text. These include locations of the modern plate boundaries, the age of the ocean floor, and a series of paleographic reconstructions. Each section begins with an overview of the learning task. For example, the modern plate boundary section begins by stating, "You will use the Web GIS to gather authentic tectonics data by making ship tracks and assessing that data to identify ridges and transforms to mark modern plate boundaries. You will connect your identified ridges and transforms to mark your plate boundaries. It is recommended that you start working in a specific map section, instead of taking on the entire map at once. Be sure to use all of your data sets." The handout then provides students with necessary procedures for labeling the plate boundaries and instructs students with some minimum guidelines for completing the activity: "Continue marking the map in the section of ocean between the two continents. You should draw at least 4 transform and 5 ridge segments on the Web GIS."

THE SIMULATION ACTIVITY

Just as Alfred Wegner speculated that South America and Africa were once connected because of the mirror images of the coastline more than a century ago, the Plate Game incorporates paired geometry across rifted boundaries (Wegner, 1912). Sedimentary basins and truncated mountains also provide clues to continent restoration. The instructor can have the students speculate on the tectonic history and then have them query their ideas against incorporated data sets. The strategy of data set exploration is framed as hypothesis testing with this approach.

In the learning activity, students conceptually explore the floor of the ocean in a virtual environment to gather tectonic data by making ship tracks (collecting data from ship board while towing traditional sensors) and assessing that data to identify ridges and transforms. To gather such data, ships must travel across the ocean accessing two-dimensional raster data sets of heat flow, bathymetry, magnetic anomalies, and sediment cores beneath an opaque layer of the ocean. In reality, scientists are limited by the costs of gathering data and only have the ability to gather data at certain depths and in limited locations. This reality is relaxed in the assignment to allow students to collect as much data on the marine geology and geophysics as they wish and to thoroughly test their suppositions in an iterative fashion.

A consistent suite of data has been built into the Web GIS. For example, in the lower right of the simulation, the learners can identify a convergent subduction plate boundary by recognizing deep epicenters of contractional earthquakes and, in appropriate fashion toward the plate boundary, a young accreted mountain range, a volcanic chain on the upper plate, trench bathymetry and sedimentation, and thick ocean sedimentation consistent with an old ocean floor with old biostratigraphy. Iteration and visualization of multiple data coverages allow students to test hypotheses against data as they progress with the assignment. Students access marine data using Web GIS and analyze that data to mark modern plate boundaries by identifying ridges, transforms, and a subduction zone. They draw ages of the ocean floor and use the isochrones to reconstruct the ancient plate configuration at 40, 60, and 80 million years ago. Students must also explain their reasoning using Web GIS screenshots and accompanied explanatory text. All assessed artifacts are submitted electronically.

In the Earth's ocean basins, ocean bottom bathymetry is related to the age of the ocean floor, heat flow, sediment thickness, and spreading rate. For most students, distinctive ridge bathymetry guides the determination of spreading centers as they constrain present-day plate boundaries. Heat flow confirms ocean-ridge identification decisions through an iterative process. Coastline parallel ship tracks help students identify transform faults by illuminating steps in ocean floor bathymetry, heat flow, and age. Magnetic anomalies, which are also a function of age, allow students to mark areas of normal and reverse polarity in the ocean basins and can be used with sediment core biostratigraphy to resolve the age of the ocean floor (Fig. 1).

The students' goal is to reconstruct ancient continental positions by first determining present-day plate boundaries and then reconstructing the age of the ocean floor from marine data sets. The synthesis of multiple data sets consistent with the multitude of lines of geological and geophysical evidence is important for completing the project. Inside the Web GIS toolbox, students use the "Add Ship Track" option to mark ship tracks anywhere on the map to investigate the subsurface in the marine basin. This action prompts a window to open that contains heat flow data, bathymetry, magnetic anomaly charts, and drill holes (Fig. 1). Placing the cursor along any of the charts shows the corresponding position along the ship track. Students can mark areas of interest along the track and charts by clicking to place different colored dots; connecting like dots facilitates determining the age of the ocean floor. On a horizontal ship track drawn perpendicular to coasts, students look for high heat, high elevation, and little sediment to locate the divergent boundaries. Students can confirm transform offsets in the ridge with north–south-oriented ship tracks, which recover steps in bathymetry and differences in heat flow that vary with age.

In the ship track window, corresponding sediment cores are shown to the right. Clicking anywhere on a ship track will access and display the corresponding sediment core (Fig. 1). Turbidities fringing continental margins are represented by a dotted pattern, and finer-grained marine sediment is shown as a dashed pattern. In keeping with reality, ages are provided sporadically within the sediment cores with irregularly spaced biostratigraphic ages at depths that are commonly drilled. Older areas will have both more sediment and an increased thickness of continental sediment, aligned with their proximity to land. The cores will have less sediment thickness, the younger the ocean floor is. Ship track data are consistent with earthquake and geologic data, allowing multiple data sets to be explored simultaneously to confirm the interpretations.

The "Query Earthquakes" option, also within the Web GIS toolbox, allows students to explore the mechanisms of earthquakes whose focal mechanisms are marked on the map. Earthquakes are marked as shallow or deep, with a corresponding magnitude shown in the pop-up image (Fig. 2). For example, shallow, extensional earthquakes are important for finding ocean ridges.

After students have successfully marked sections of ocean into ridges and transforms, they must complete the determination of the present-day plate boundaries, at age 0 Ma. A convergent boundary lies just oceanward of the ocean island arc. The youngest mountains mark the locus of the plate collision, a bathymetric trench with sediment fill, and deep-focus earthquakes that delineate the down-going slab verging east from the plate boundary. Using the "Editor" toolbox, students can draw in ridges and transforms. Once students are confident of an age on the ocean floor, they can use the "Editor" toolbox to draw in lines of various colors that correspond to different ages. Ultimately, students will have a map covered in age isochrones (Fig. 3). The difference in spacing of the isochrones is indicative of varying spreading rate. Age contours that are more widely spaced and have a gentler ridge-crest morphology are indicative of a faster spreading rate and are associated with broader ocean ridges. Finally, students highlight continental boundaries to rotate and move plates to ancient positions, according to the age of the ocean floor.

EVIDENCE OF EFFECTIVENESS

The Web GIS plate tectonics simulation was implemented in the Spring 2015 EES223 Structural Geology and Tectonics course. The course is a major elective for either the BA or BS degree in Earth and Environmental Sciences (EES). The class in 2015 consisted of 13 students: 1 sophomore female, 4 junior females, 4 senior females, 2 senior males, and 2 fifth-year females who were completing the EES double-degree BS after finishing their BS degree in Environmental Engineering. A senior male was completing a double major in EES with an Environmental Studies BA, and one senior female completed the Environmental Studies minor with a BS in EES. The class had a teaching assistant to

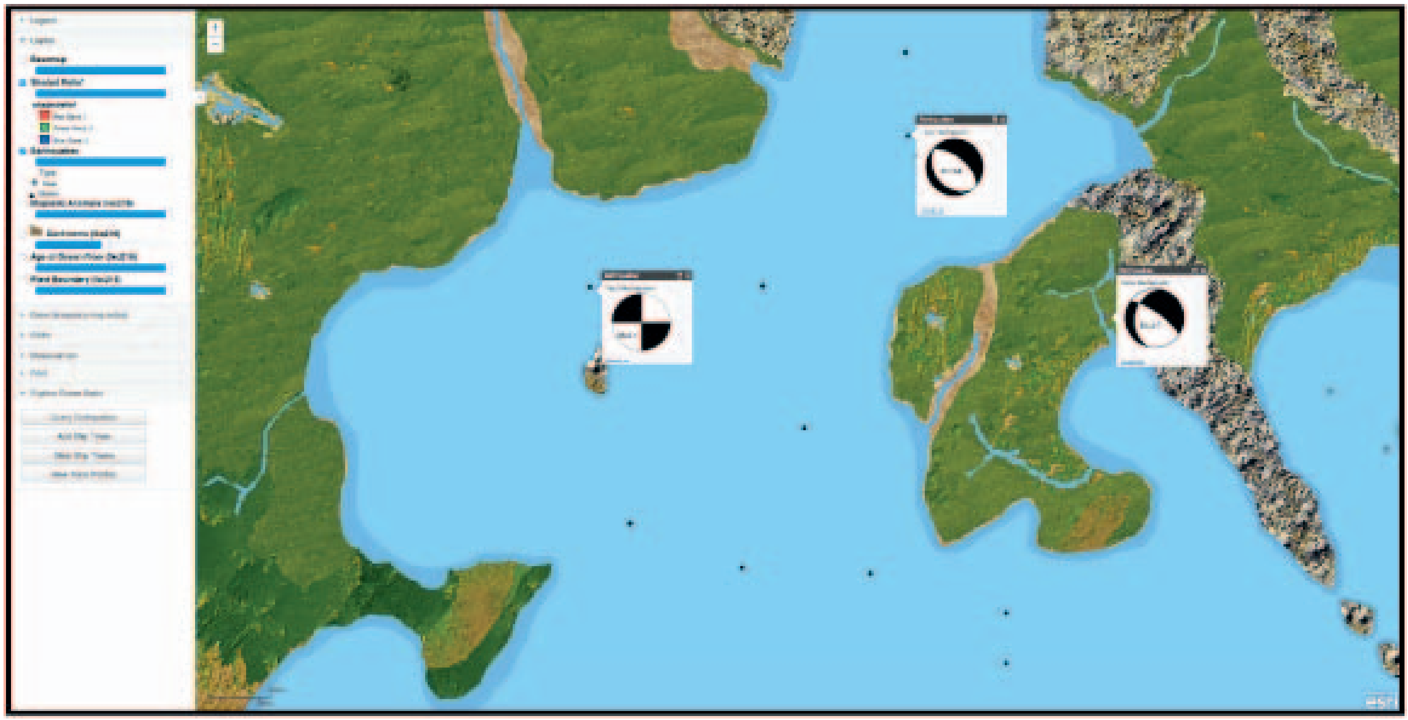

FIGURE 2: Base map showing epicenters and first-motion focal mechanisms. Legend indicates fault types for first-motion stereonets.

assist with the laboratory exercises. Coauthor and class student R.S. led the Plate Game instruction. She did not participate in the survey results reported in the manuscript. The Web GIS was completed in partial fulfillment of a full-year research project by R.S.

To assess the effectiveness of the Web GIS plate tectonics, all 12 students in the course submitted three artifacts. These were Web GIS screen shots of the modern plate boundaries, an age of the ocean screenshot with isochron drawings, and continent reconstructions at 20, 40,

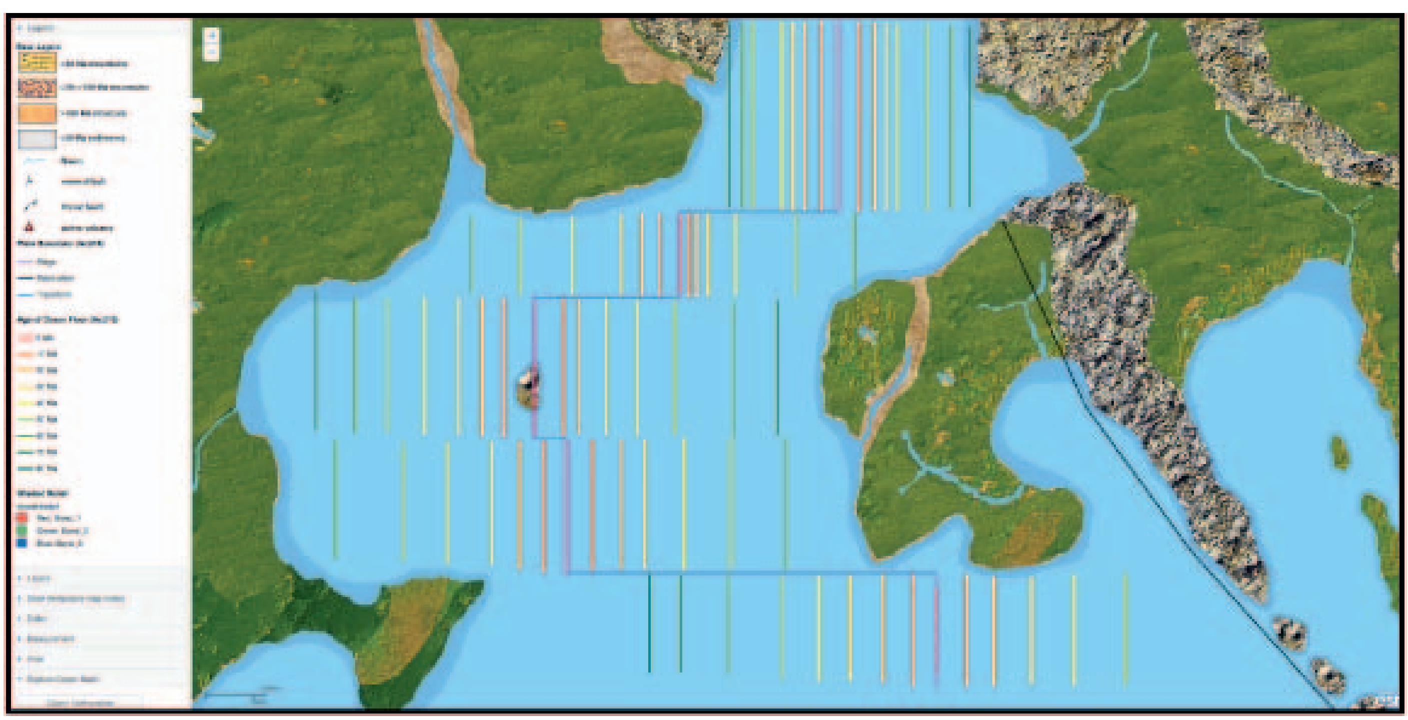

FIGURE 3: Age of the ocean isochrons and plate boundary interpretations. The isochrones are derived from magnetic anomaly patterns and sediment core interpretations used to determine the age of the underlying oceanic crust. Legend shows ocean crust ages.

Plate Game Rubric

Criteria	Exemplary (4)	Proficient (3)	Adequate (2)	Needs Improvement (1)
Modern plate boundaries are marked on Web GIS map.	Each type of available plate boundary is marked on the map, includes ridge, transform, and subduction. The entire map is divided up. The subduction zone is to the East of the volcanic island arc, and not on top of it.	All available plate boundaries are marked on the map, including ridge, transform, and subduction. The entire map is divided up. The subduction zone is to the East of the volcanic island arc, and not on top of it.	Some ridges and transforms are diagonal. The entire map is divided up. The subduction zone is marked to the West of the volcanic island arc.	Ridges and transforms may be diagonal. The subduction zone is marked on top of the volcanic island arc or the deep, compressive earthquakes. The map is incompletely marked.
Isochrons are drawn onto Web GIS map.	Isochrons cover the full extent of the map, in the range of 80 Ma to 0 Ma in 10 million year intervals. Lines follow the modern plate boundaries and are consistent with one another.	Isochrons cover the full extent of the map, in the range of 80 Ma to 0 Ma. Lines follow the modern plate boundaries and are consistent with one another.	Isochrons cover most of the map. The gaps may exceed 10 million years, but the isochrons are still consistent with each other.	Map is incompletely marked with isochrons. There are many inconsistencies between isochrons.

Criteria	Exemplary (4)	Proficient (3)	Adequate (2)	Needs Improvement (1)
Continents are reconstructed to their paleogeographic locations.	Three separate images show continents at proper locations at 40, 60, and 80 Ma. Ocean closes before youngest continent detaches. Youngest continent shifts into proper ancient position.	Three separate images show continents at proper locations at 40, 60, and 80 Ma. Ocean closes before youngest continent detaches.	Three separate images show continents at proper locations at 40, 60, and 80 Ma.	Does not include each of the reconstructions. Youngest continent has not shifted, or ocean has not closed.
Concise explanation of thought process and what tools were used to make decisions.	Report includes at least one screenshot for each deliverable. Each screenshot is thoroughly explained, and the thought process is logical and repeatable.	Report includes at least one screenshot for each deliverable. The thought process is logical and repeatable.	Report includes at least one screenshot for each deliverable, with an accompanying explanation. Logic may be incorrect.	Report includes screenshots with no explanation text, or explanation text with no screenshots. Logic may be incorrect.

FIGURE 4: Criterion-based rubric to assess the learning activity.

60, and 80 Ma. With each artifact, students were required to provide textual justifications containing supporting evidence and data from the Web GIS. The artifacts were assessed using a criterion-based rubric (Fig. 4). The rubric was designed to measure student achievement in their accuracy of identifying modern plate boundaries, the placement of isochrones, and the plausibility of continent reconstructions. The student artifacts were scored by two independent raters who were involved with the course development to ensure that the correct criteria would be applied to assess the submitted artifacts. The two raters coded each artifact independently for reliability and were found to be in agreement 93% of the time before discussion. Any discrepant cell placements on the rubric were resolved via discussions between the coders. The students also completed a survey to assess their perceptions of the effectiveness of the online interface and its capability to promote geospatial thinking. The survey items are included in the Appendix A.

The students performed remarkably well on the assignments. No student scored less than proficient in any criteria on the rubric scoring. Most student-artifact submissions were generally accurate, and some submissions were outstanding and included detailed reasoning for the continent placements on the ancient map reconstructions. All students were able to accurately mark the modern plate boundaries and the age of the ocean floor. Fig. 5 shows an example of a submitted student artifact. The submitted artifact in Fig. 5 shows modern plate boundaries and

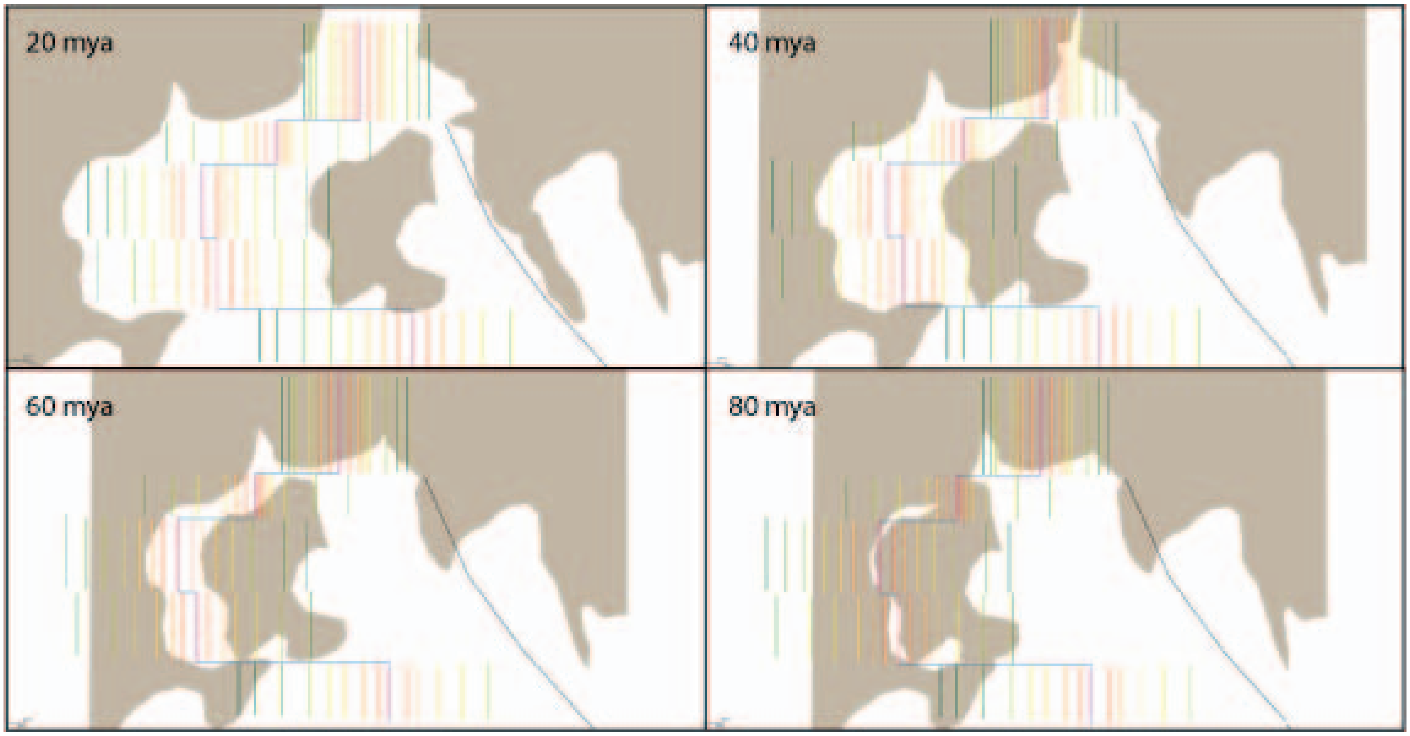

FIGURE 5: Plate reconstructions at 20, 40, 60, and 80 Ma. Students rationalize their reconstructions in writing to accompany their reconstructions.

isochrones on the ocean floor used to reconstruct the plate configuration at 20, 40, 60, and 80 Ma. The symmetry of the isochrones supports the student's interpretation. The variation in the spacing of the isochrones is reflective of variations in ocean-spreading rates along the ocean basin. Students translated the plates to reflect past plate configurations and also dynamically rotated or distorted the plates as desired.

The responses from the student survey were quite positive. All students found the Web GIS tectonics simulation to be engaging, and eight (67%) stated that they would prefer more laboratory activities in this style. When asked whether they believed the Web GIS investigation enhanced what they typically do in their university classroom when they learn about tectonics, all but one student responded "yes." The students identified many features of the Web GIS interface in response to the survey item that asked the students what they liked about the learning activity. The students particularly liked the interactive mapping features of the Web GIS and commented on how it assisted with their learning. It enabled the students to "explore more and take more risks." The Web GIS enabled them to physically move plates around in the Web GIS environment. Some students also noted that the Web GIS helped them to visualize and think through the concepts that were taught in the classroom. The students also commented that the Web GIS allowed them to correct their mistakes and dynamically change their reconstructions with relative ease when completing the learning tasks. During the laboratory period, the students were guided by the course instructor and teaching assistant during assignment completion. Inevitably, the students tested their evolving ideas with additional data to refine their interpretations. Inconsistent data caused students to revise their interpretations until internal consistency was achieved. The students noted that they enjoyed working at their own pace, enjoyed the exploratory nature of the learning activity, and found the Web GIS interface easy to use. The students also enjoyed the visualizations they produced during the learning task. One student commented, "I enjoyed seeing how all the work I did with the ship tracks actually applies to reconstruction of continents." Another student liked "having to think more critically about the characteristics of the sea floor and what it means." A different student enjoyed "being able to visualize the fault boundaries from the earthquake and the heat data," and another stated, "I liked reconstructing the age of the ocean floor and the continent reconstruction."

The survey results supported that the Web GIS tectonics simulation helped students think geospatially. Table II displays select student responses when asked, "In what ways do learning about tectonics with the Web GIS mapping and analysis tools help you think geospatially?" The responses indicated that the Web GIS supported students' geospatial analysis for making inferences about space, geospatial patterns, and geospatial relationships among the data that were visualized in the Web GIS. This was especially helpful for geospatial relationships among heat flow, bathymetry, age of sediment, and magnetic anomalies. The Web GIS tool features helped the students use inductive and deductive reasoning to analyze, synthesize, compare, and interpret the data within the Web GIS.

Students were on task and actively engaged during the two 3-hour computer-laboratory sessions when they used the Web GIS tectonics simulation. Most students worked approximately five hours during the two class sessions. Seven (58.3%) students reported that they completed the assignment without any additional time outside of the class laboratory hours. Three (25.0%) students required up to an

TABLE II: Select student survey responses about how the Web GIS helped students think geospatially.

It allows students to be able to visualize how the earth's plates have moved over time and how tectonics affect the earth. It also gives a hands-on, problem-solving opportunity to learn about it instead of just listening and seeing it.
I learned how to recognize where the different plate boundaries exist; this lab also helped to visualize how the different types of plate boundaries are placed with relation to one another and consequently where the different aged rocks are placed. It was helpful to physically move the continents to their respective places with time as well.
It helps me to envision the movement of things that otherwise would be demonstrated on a piece of paper or chalk board. The visualization really helps driving the point home.
This mapping exercise helped me think geospatially by analyzing the data I created. After I created the ridges, transforms, ocean ages, and continent reconstruction I was able to analyze what this data meant in terms of plate tectonics.
It enabled me to see and work with the connections between magnetic anomalies, age, rock layer, and age.

additional hour to complete the learning activity outside of the laboratory periods. One (8.3%) student reported needing 1–2 additional hours to complete the activity, and one student (8.3%) reported needing 2–3 more hours to complete the activity.

During the implementation, the students experienced some technical issues during the first day with the Web GIS and noted these in their survey responses on what they did not like about the learning activity. These issues were resolved by the second laboratory session. The students also identified some interface issues with the Web GIS simulation in their survey responses. Five students (41.7%) noted that the continents did not perfectly fit together after they had been rotated. Three (25.0%) students stated that they did not like having to open up a ship track profile to view the drill core. Two students (16.7%) commented that they wished they could delete one ship track path at a time instead of having to delete an entire batch of ship track lines all at one time.

DISCUSSION

Learning with a Web GIS simulation provides a novel approach to learning about tectonics and an excellent assessment tool for plate tectonic content. We think that the Web GIS tectonics simulation was more engaging for our students compared with the paper-and-pencil plate tectonics simulation that was used during the past years of the course. We make this assessment based on observations of individual student focus and longevity of uninterrupted time on task. An appropriately designed Web GIS has the capability to promote geospatial thinking in ways that seem to be much richer than using typical paper-based learning activities that are often used to teach related concepts in undergraduate Earth Science courses. The implementation of the Web GIS tectonics simulation with our undergraduate students resulted in a favorable student response and high student engagement during the learning activities. The Web GIS provided students with more opportunities to explore and analyze authentic-type data using geospatial thinking skills and to test their hypothesis against additional data during assignment completion. Compared with prior decades, in which a paper-based exercise was used to teach related concepts, students completed the Web GIS much faster, and we think they had greater understanding about the geospatial relationships in the data. For example, Fig. 6 contrasts a typical Web GIS student artifact with a typical student artifact from a previous paper submission. The Web GIS deliverable is of higher quality. Common misconceptions using a business-as-usual, paper-based approach nearly always included students who chose ridge positions that were asymmetrical with respect to magnetic anomalies. These included ridge segment interpretations that were not parallel or orthogonal to transform segments and/or failed to include an unrestored microcontinent and continent plate boundaries. The use of the Web GIS tool, which allowed continental areas to be manipulated, resulted in ubiquitous and more-appropriate accretionary peninsula restoration (Fig. 6). Students in previous years required a full 3-hour laboratory period with approximately 6 hours of work outside of class over a period of 12 days; the average time to completion was approximately 9 hours with the paper and pencil simulation. Students completed the Web-based simulation activity in less time, with a greater proficiency, and with greater understanding. Given the quality of the student deliverables and shortened completion time, the instructor feels no changes were warranted. The Web GIS assignment was deemed appropriate for teaching and testing advanced undergraduate tectonics content.

The submitted student artifacts provided evidence that the students used important geospatial thinking skills during the simulation. Students used the Web GIS for making inferences about space, geospatial patterns, and geospatial relationships related to the tectonics data. The Web GIS provided students with a way to examine geological and geophysical data to reveal patterns and relations about the Earth's surface that may not have been readily apparent using a paper-based simulation activity. During the learning activities, the students created multiple visualizations that they used to organize and understand the different geological and geophysical data. The task of identifying modern plate boundaries required analyzing geospatial visualizations and geospatial relations to identify ridges, transforms, and subduction zones.

We contend that learning with a Web GIS simulation was effective because the learning activity was an authentic simulation, and the Web GIS provided a user-friendly interface and tool set. The assignment was rich in data and visualizations that helped students understand important geospatial patterns and relationships. Our Web GIS design and embedded capabilities allowed students to confirm their understandings about the tectonics concepts. The students could revise their explorations, try out new ideas to explore geospatial patterns and relations in the data, and confirm their conclusions with data supported through their Web GIS investigations. As a result, the learning activity provided multiple opportunities for immediate self-assessment, thus providing learners with enhanced learning opportunities.

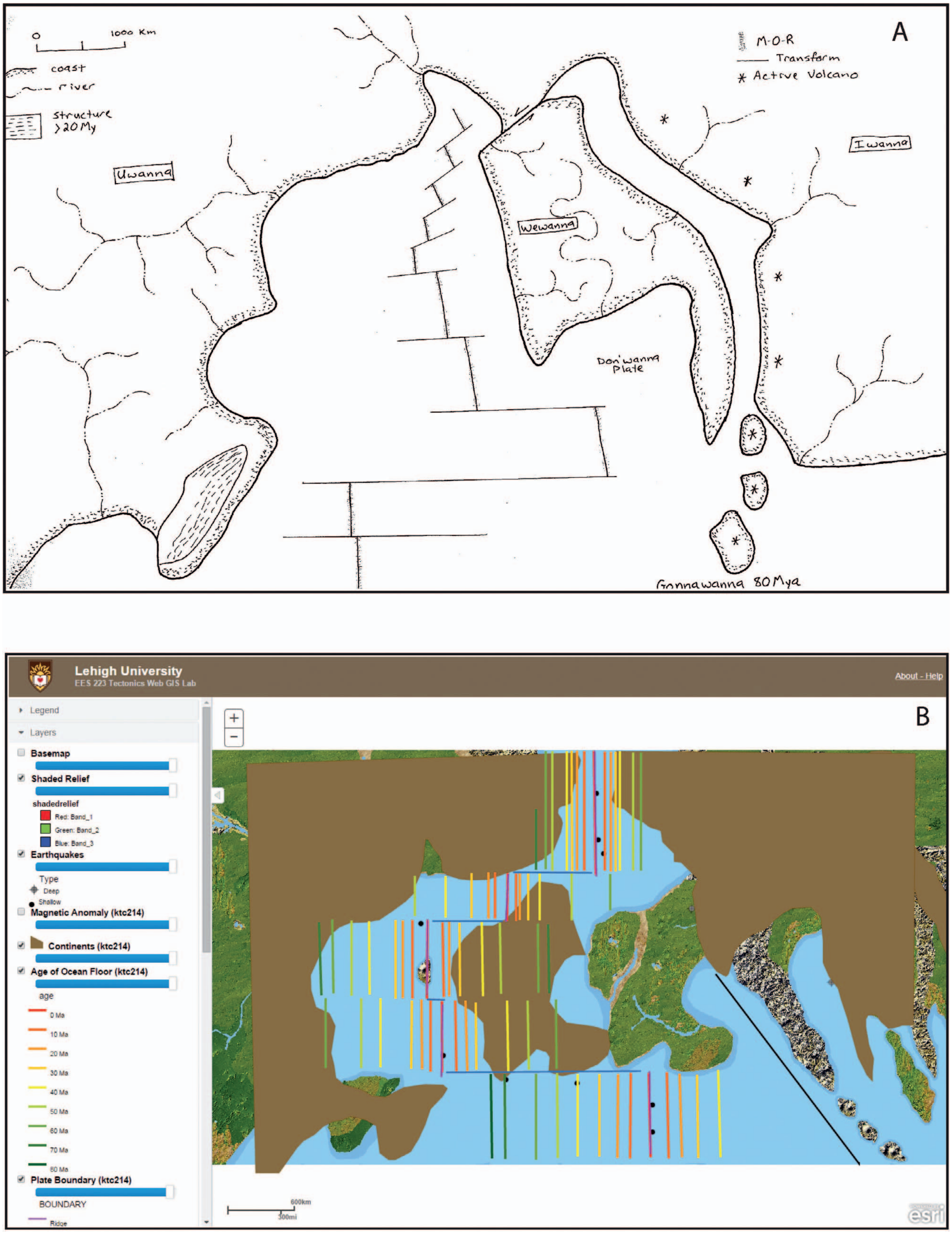

FIGURE 6: Examples of student artifacts. (A) Older artifact of a 20-Ma reconstruction produced by hand. Inconsistencies include the location of the ridge relative to the western continent, the western coastline shape of the microcontinent, the lack of the subduction zone, and the labeled age of the reconstruction. (B) Web GIS–based reconstruction for 40 Ma. Student artifact correctly places the midocean ridge relative to the continents and correctly uses the age of the ocean isochrones to restore the continents.

Another factor that may have contributed to the success of the learning activity was the use of appropriate scaffolding in the instructional materials that was designed to assist students with geospatial analyses during the simulation. We believe that the scaffolding within the instructional materials themselves, in addition to the classroom modeling by the course instructor, was helpful in assisting the students with completing the geospatial analysis tasks. Helpful scaffolds and modeling in the students' instructional materials included prompts to focus learners on specific geospatial aspects of the Web GIS data displays, screen captures of the Web GIS interfaces to assist learners with procedures, and instructional prompts and suggestions for manipulating the tools to assist with geospatial pattern finding and data analysis.

Our belief is that the embedded scaffolding makes the learning activities accessible to students in an introductory course once the class has covered the topics of volcanism, seismicity, and plate boundaries. The introductory sections of the instructional handout were designed to be very guided and have learners follow a set of procedural steps with accompanied images to observe topography and access and understand the marine data, earthquake data, and sediment cores. The most difficult concept for students in an introductory course to understand may be stratigraphy from sediment cores, a topic not normally covered by Earth System Science of Physical Geology classes. With the inclusion of appropriate conceptual and procedural scaffolds, in addition to effective modeling by the course instructor, the Web GIS activity can be used in introductory courses or as a free-standing tutorial.

There are some limitations to our findings. First, our sample size was quite small and represents a select population of undergraduate EES majors at a private, undergraduate institution. Therefore, the findings cannot be generalized to other populations. Second, the data that supports the effectiveness of the Web GIS to promote geospatial thinking skills included student self-reported data. Although the submitted artifacts by the students involved certain geospatial thinking skills that were measured with a valid and reliable criterion-based rubric, we did not administer any standard-based psychometric spatial skills tests that have been used in previous studies (see, e.g., Kali and Orion, 1996; Titus and Horseman, 2009). Therefore, we are unable to compare specific spatial thinking abilities to that of other university-level students who have used other forms of tectonics instruction.

CONCLUSION

The Web GIS tectonics simulation is a learning activity that provided an enhanced learning environment to help students understand important tectonics concepts while using important geospatial thinking skills. Web GIS can be designed to have a user-friendly interface and tool set to empower learners to better understand geospatial patterns and geospatial relationships among authentic Earth Science data using dynamic mapping. Web GIS learning activities designed with appropriate scaffolding can provide for more enhanced learning compared with paper-based simulation activities that are more typically used in undergraduate Earth Science courses.

SUPPLEMENTAL MATERIAL

Note: The Web GIS tectonics simulation and instructional materials are freely available at http://gisweb.cc.lehigh.edu/ees223/. Users will not be able to save their work with this version.

Acknowledgments

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APPENDIX A

Survey to assess the effectiveness of the Web GIS tectonics simulation

1. Did you find the Web GIS lab simulation engaging?

Yes

No

Other:

2. Approximately how much time did you spend on this assignment outside of the lab hours?

.5 hour to 1 hour

1 hour to 2 hours

2 hours to 3 hours

3 hours to 4 hours

More than 4 hours

3a. In the Earth and Environmental Sciences, geospatial thinking and reasoning typically involves geospatial analysis and interpretation of maps, models, diagrams, and charts, and interpretation and manipulation of data obtained from same. In what ways do learning about tectonics with the Web GIS mapping and analysis tools help you think geospatially?

3b. Can you provide some examples from the investigations you performed?

4a. Do you believe that the Web GIS investigation enhanced what you typically do in your university classroom when you learn about tectonics?

No

Yes

Somewhat

4b. If you responded ''somewhat'' or ''yes,'' please describe how.

5. List 3 things that you liked about this learning activity.

6. List 3 things that you did not like about this learning activity.

7. Would you prefer more or fewer labs in this format (i.e., online map to explore)?

More labs like this.

Fewer labs like this.